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THE HOST GALAXIES OF SHORT-DURATION GAMMA-RAY BURSTS: LUMINOSITIES, METALLICITIES, AND STAR FORMATION RATES

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ABSTRACT

The association of some short-duration gamma-ray bursts (GRBs) with elliptical galaxies established that their progenitors, unlike those of long GRBs, belong to an old stellar population. However, the majority of short GRBs appear to occur in star forming galaxies, raising the possibility that some progenitors are related to recent star formation activity. Here we present optical spectroscopy of these hosts and measure their luminosities, star formation rates, and metallicities. We find luminosities of $L_B \approx 0.1-1.5\ L_*$, star formation rates of SFR $\approx 0.2-6\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$, and metallicities of $12+\log(\mathrm{O/H}) \approx 8.5-8.9$ ($Z \approx 0.6-1.6\ Z_\odot$). A detailed comparison to the hosts of long GRBs reveals systematically higher luminosities, lower specific star formation rates (SFR$/L_B$) by about an order of magnitude, and higher metallicities by about 0.6 dex. The K-S probability that the short and long GRB hosts are drawn from the same underlying galaxy distribution is only $\sim 10^{-3}$. On the other hand, short GRB hosts exhibit excellent agreement with the specific star formation rates and the luminosity-metallicity relation of field galaxies at $z \sim 0.1-1$. We thus conclude that short GRB hosts are not dominated by young stellar populations like long GRBs hosts. Instead, short GRB hosts appear to be drawn uniformly from the underlying galaxy distribution, indicating that the progenitors have a wide age distribution of several Gyr.

Subject headings: gamma-rays:bursts

1. INTRODUCTION

The properties of gamma-ray burst (GRB) host galaxies provide important insight into the nature of the burst progenitors. In the case of the long-duration GRBs ($T_{90} \gtrsim 2$ s), the hosts are blue star forming galaxies with high specific star formation rates and sub-L_* luminosities (e.g., Hogg & Fruchter 1999; Chary et al. 2002; Berger et al. 2003; Le Floc'h et al. 2003; Christensen et al. 2004; Savaglio et al. 2008). Moreover, the bursts themselves trace the star formation activity within their hosts (Bloom et al. 2002; Fruchter et al. 2006). At low redshift, $z \lesssim 0.3$, long GRBs appear to occur preferentially in low luminosity and metallicity galaxies (Stanek et al. 2006; Savaglio et al. 2008), although it remains unclear whether this is a causal connection or a byproduct of the intense star formation activity (Berger et al. 2007a). Taken together, these properties provided an early indication that the progenitors of long GRBs are massive stars, and ultimately they may shed light on the conditions (if any) that favor the formation of the progenitors.

The more recent discovery of afterglow emission from short-duration GRBs led to associations with both star forming and elliptical host galaxies (Berger et al. 2005; Fox et al. 2005; Gehrels et al. 2005; Bloom et al. 2006). The association with elliptical galaxies demonstrates unambiguously that the progenitors of at least some short GRBs are related to an old stellar population, consistent with the popular model of compact object mergers (NS-NS or NS-BH; e.g., Eichler et al. 1989; Narayan et al. 1992). In addition, *Hubble Space Telescope* imaging of the star forming host galaxy of GRB 050709 revealed that, unlike in the case of the long GRBs, the burst was not associated with a region of active star formation (Fox et al. 2005).

Subsequent to the discovery of the first short GRB afterglows and hosts, we have shown that a substantial fraction of these events (1/3 – 2/3) reside at higher redshifts than previously suspected, $z \gtrsim 0.7$ (Berger et al. 2007b; Cenko et al. 2008). Spectroscopic observations indicate that a substantial fraction of these galaxies are undergoing active star formation. Indeed, of the current sample of short GRBs localized to better than a few arcseconds (23 bursts), $\approx 45\%$ reside in star forming galaxies compared to only $\approx 10\%$ in elliptical galaxies[3]. This result raises the question of whether some short GRBs are related to star formation activity rather than an old stellar population, and if so, whether the star formation properties are similar to those in long GRB host galaxies. The answer will shed light on the diversity of short GRB progenitors, in particular their age distribution and the possibility of multiple progenitor populations.

Here we present optical spectroscopy of short GRB host galaxies and measure their luminosities, metallicities, and star formation rates (§2 and §3). We then assess their specific star formation rates and luminosity-metallicity relation, and compare these results with the properties of long GRB hosts and field star forming galaxies (§4). Finally, we use these comparisons to draw conclusions about the progenitor population, and we outline future host galaxy studies that will provide continued constraints on the progenitors (§5). Throughout the paper we use the standard cosmological parameters, $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

2. OBSERVATIONS

In Table 1 we summarize the properties of all short GRBs with *Swift* X-ray Telescope (XRT) localizations, and their host galaxies. All references for the burst and host properties are provided in Table 1, including in particular Berger et al. (2007b) and Cenko et al. (2008) for the details of our spectroscopic observations. We present the flux-calibrated spectra of the host galaxies of GRBs 060801, 061006, 061210, 061217, and 070724 in Figure 1. Spectra of the hosts of GRBs

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[3] The other $\approx 45\%$ remain currently unclassified due to their faintness, a lack of obvious spectroscopic features, or the absence of deep follow-up.

070429b and 070714b are presented in Cenko et al. (2008), while spectra of the hosts of GRBs 050709 and 051221a are provided in Fox et al. (2005) and Soderberg et al. (2006), respectively. Below we summarize our new spectroscopic observations of GRB 070724.

2.1. *GRB 070724*

A putative host galaxy was identified within the 2.2″ radius XRT error circle of this short burst in archival Digital Sky Survey images (Bloom & Butler 2007). No coincident variable optical, near-IR, or radio source was detected (Levan et al. 2007; Cucchiara et al. 2007; Covino et al. 2007; Chandra & Frail 2007).

We obtained imaging and spectroscopy of the likely host galaxy using the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) mounted on the Gemini-South 8-m telescope. We confirm the presence of the galaxy and measure its brightness to be $r_{\rm AB} = 20.56 \pm 0.03$ mag. The probability of chance coincidence for a galaxy of this brightness within the XRT error circle is only 8×10^{-3} (Beckwith et al. 2006).

The spectroscopic observations lasted a total of 3600 s, using the GMOS R400 grating at central wavelengths of 7000 and 7050 Å with a 1″ slit (resolution of about 7 Å). The data were reduced using the `gemini` package in IRAF. Wavelength calibration was performed using CuAr arc lamps and air-to-vacuum and heliocentric corrections were applied. We identify several emission lines corresponding to [OII]λ3727, [OIII]$\lambda\lambda$4959, 5007, and Hβ at a redshift of $z = 0.4571 \pm 0.0003$ (Figure 1).

3. HOST GALAXY PROPERTIES

The sample of short GRBs presented in this paper is comprised of all events with *Swift*/XRT positions (23 bursts), with typical uncertainties of $\sim 2-5''$ (Butler 2007; Goad et al. 2007). Of these events, nine bursts have been further localized to sub-arcsecond precision based on detections in the optical, near-IR, radio, and/or X-rays. In eight of these nine cases a host galaxy has been identified[4], and in six cases its redshift has been measured. These are the most secure host galaxy associations in the sample, with a redshift range of $z \approx 0.16-0.92$, an optical magnitude range of $r \approx 18-25$ mag, and a ratio of late- to early-type of 5 : 1 (hereafter, *Sample 1*). The additional two bursts with sub-arcsecond positions and no current redshift measurements have faint hosts with $r = 24.8$ and 26.3 mag. As discussed in Berger et al. (2007b), these events are likely located at $z \gtrsim 0.7$.

Of the 14 short bursts with only XRT positions, 12 have deep follow-up observations that led to the identification of galaxy counterparts, with $r \approx 17-26$ mag; the chance coincidence probabilities for these galaxy associations range from $\sim 10^{-3}$ to 0.1 (for a detailed discussion see Berger et al. 2007b). Six of these 12 hosts have spectroscopically measured redshifts, $z \approx 0.23-1.13$ (hereafter, *Sample 2*). These are the brighter hosts, $r \approx 17-23$ mag, and their probabilities of chance coincidence are thus the lowest (Berger et al. 2007b). Their ratio of late- to early-type is again 5 : 1. The remaining, fainter hosts likely reside at $z \gtrsim 0.7$ (Berger et al. 2007b).

We focus here on the two samples of host galaxies with measured spectroscopic redshifts. As we stress below, our results remain unaffected even if we use only the events with sub-arcsecond positions (*Sample 1*).

3.1. *Luminosities*

We infer the host galaxy absolute magnitudes in the rest-frame B-band, M_B, using their observed r-band magnitudes (Table 1). At $z \lesssim 0.5$ the observed r-band directly samples the rest-frame B-band, but for the hosts at $z \sim 1$ it provides a measure of the rest-frame U-band. To transform the latter to the B-band we use the typical rest-frame $U-B$ colors of blue galaxies, appropriate for our star forming galaxy sample, as measured from the DEEP2 galaxy survey, $U-B \approx 0.75$ mag (Coil et al. 2008). The observed dispersion in $U-B$ color results in a $\sim 30\%$ uncertainty in M_B.

For the hosts in *Sample 1* we find $M_B \approx -18$ to -21 mag, or $L_B \approx 0.1-1.5\, L_*$; the highest luminosity belongs to the elliptical host galaxy of GRB 050724 (Berger et al. 2005). We use the appropriate value of L_* as a function of redshift determined from the DEEP2 survey (Willmer et al. 2006). For the star forming hosts in *Sample 2* we find $M_B \approx -20$ to -21 mag, or $L_B \approx 0.4-1.4\, L_*$; the elliptical host galaxy of GRB 050509b has $L_B \approx 5\, L_*$ (Bloom et al. 2006). The distribution of M_B values is shown in Figure 2.

3.2. *Star Formation rates*

We next use the [OII]λ3727 line luminosities to infer the host star formation rates (Figure 1). We use the standard conversion, SFR = $(1.4 \pm 0.4) \times 10^{-41} L_{\rm [OII]}$ M$_\odot$ yr^{-1} (Kennicutt 1998). For the star forming hosts in *Sample 1* we find SFR $\approx 0.2-1$ M$_\odot$ yr^{-1}, while the elliptical host of GRB 050724 has SFR $\lesssim 0.05$ M$_\odot$ yr^{-1} (Berger et al. 2005). For the galaxies in *Sample 2* we infer SFR $\approx 1-6$ M$_\odot$ yr^{-1}, with a limit of $\lesssim 0.1$ M$_\odot$ yr^{-1} for the elliptical host of GRB 050509b (Bloom et al. 2006). The star formation rate for each host galaxy is provided in Table 1.

Using the absolute magnitudes inferred above, we find that the specific star formation rates are SFR$/L_B \approx 1-10$ M$_\odot$ yr^{-1} L_*^{-1} for the star forming hosts; see Figure 3. For the two elliptical host galaxies the upper limits are SFR$/L_B \lesssim 0.03$ M$_\odot$ yr^{-1} L_*^{-1}.

3.3. *Metallicities*

For five of the twelve host galaxies we have sufficient spectral information to measure the metallicity[5]. We use the standard metallicity diagnostics, $R_{23} \equiv (F_{\rm [OII]\lambda3727} + F_{\rm [OIII]\lambda\lambda4959,5007})/F_{\rm H\beta}$ (Pagel et al. 1979; Kobulnicky & Kewley 2004) and $F_{\rm [NII]\lambda6584}/F_{\rm H\alpha}$. The value of R_{23} depends on both the metallicity and ionization state of the gas, which we determine using the ratio of oxygen lines, $O_{32} \equiv F_{\rm [OIII]\lambda\lambda4959,5007}/F_{\rm [OII]\lambda3727}$.

We note that the R_{23} diagnostic is double-valued with low and high metallicity branches (e.g., Kewley & Dopita 2002). This degeneracy can be broken using [NII]/Hα when these lines are accessible. To facilitate a subsequent comparison with field galaxies (§4) we use the R_{23}, O_{32}, and [NII]/Hα calibrations of Kobulnicky & Kewley (2004) (their Equations 12 and 18). We note that the typical uncertainty inherent in the calibrations is about 0.1 dex.

The line fluxes for the five short GRB hosts, and the resulting values of R_{23} and O_{32} are provided in Table 2.

[4] The single exception is GRB 070707 for which our deepest limit is $r \gtrsim 24.4$ mag.

[5] The relevant emission lines are [OII]λ3727, Hβ, [OIII]$\lambda\lambda$4959, 5007, Hα, and [NII]λ6584.

We adopt the solar metallicity from Asplund et al. (2005), $12+\log(\mathrm{O/H}) = 8.66$. For the host of GRB 061006 we find $12+\log(\mathrm{O/H}) \approx 8.6$ for the upper R_{23} branch and $\approx 8.0-8.5$ for the lower branch. For the host of GRB 070724 we find $12+\log(\mathrm{O/H}) \approx 8.9$ for the upper branch, and $\approx 7.6-8.1$ for the lower branch. We find a similar range of values for the host of GRB 061210, but the ratio $F_{[\mathrm{NII}]}/F_{\mathrm{H}\alpha} \approx 0.2$, indicates $12+\log(\mathrm{O/H}) \gtrsim 8.6$, thereby breaking the degeneracy and leading to the upper branch solution, $12+\log(\mathrm{O/H}) \approx 8.9$.

For the previously-published host of GRB 051221a we use the line fluxes provided in Soderberg et al. (2006), and derive similar values to those for the host of GRB 070724. Finally, for the host galaxy of GRB 050709 we lack a measurement of the [OII] emission line, and we thus rely on [NII]/Hα to infer[6] $12+\log(\mathrm{O/H}) \approx 8.5$. The dominant source of uncertainty in this measurement is the unknown value of O_{32}, but using a spread of a full order of magnitude results in a metallicity uncertainty of 0.2 dex.

For the hosts with double-valued metallicities (GRBs 051221a, 061006, and 070724) we follow the conclusion for field galaxies of similar luminosities and redshifts that the appropriate values are those for the R_{23} upper branch (Kobulnicky & Kewley 2004). This conclusions was advocated by Kobulnicky & Kewley (2004) based on galaxies in their sample with measurements of both R_{23} and [NII]/Hα. It is similarly supported by our inference for the host galaxy of GRB 061210. The metallicities as a function of host luminosity are shown in Figure 4.

4. A COMPARISON TO LONG GRB HOST GALAXIES AND FIELD GALAXIES

To place the host galaxies of short GRBs in a broader context we now turn to a comparison of their properties with those of long GRB hosts and field star forming galaxies at a similar redshift range. For the field sample we use the ≈ 200 emission line galaxies at $z \approx 0.3-1$ from the Great Observatories Origins Deep Survey-North (GOODS-N) field studied spectroscopically as part of the Team Keck Redshift Survey (Kobulnicky & Kewley 2004). We select this sample due to its large size, availability of luminosity, metallicity, and star formation rate measurements, and because its limiting magnitude for spectroscopy is similar to that for the short GRB host galaxies.

A comparison of the *B*-band absolute magnitude distributions of short and long GRB hosts in the same redshift range ($z \lesssim 1.1$) is shown in Figure 2. The long GRB hosts range from $M_B \approx -15.9$ to -21.9 mag, with a median value of $\langle M_B \rangle \approx -19.2$ mag ($\langle L_B \rangle \approx 0.2\ L_*$; (Berger et al. 2007a)). Thus, the long GRB hosts extend to lower luminosities than the short GRB hosts, with a median value that is about 1.1 mag fainter. A Kolmogorov-Smirnov (K-S) test indicates that the probability that the short and long GRB hosts are drawn from the same underlying distribution is 0.1. On the other hand, a comparison to the GOODS-N sample reveals a similar distribution, and the K-S probability that the short GRB hosts are drawn from the field sample is 0.6.

We reach a similar conclusion based on a comparison of specific star formation rates. For long GRB hosts the inferred star formation rates range from about 0.2 to 50 M$_\odot$ yr^{-1}, and their specific star formation rates are about $3-40$ M$_\odot$ yr^{-1} L_*^{-1}, with a median value of about 10 M$_\odot$ yr^{-1} L_*^{-1} (Christensen et al. 2004). As shown in Figure 3, the specific star formation rates of short GRB hosts are systematically lower than those of long GRB hosts, with a median value that is nearly an order of magnitude lower. Indeed, the K-S probability that the short and long GRB hosts are drawn from the same underlying distribution is only 3.5×10^{-3}. This is clearly seen from the cumulative distributions of specific star formation rates for each sample (inset of Figure 3).

On the other hand, a comparison to the specific star formation rates of the GOODS-N field galaxies reveals excellent agreement (Figure 3). The K-S probability that the short GRB hosts are drawn from the field galaxy distribution is 0.6. This result remains unchanged even if we use only the host galaxies in *Sample 1*. Thus, short GRB hosts are drawn from the normal population of star forming galaxies at $z \lesssim 1$, in contrast to long GRB hosts, which have elevated specific star formation rates, likely as a result of preferentially young starburst populations (Christensen et al. 2004; Savaglio et al. 2008).

Finally, the metallicities measured for short GRB hosts are in excellent agreement with the luminosity-metallicity relation for field galaxies at $z \sim 0.1-1$ (Figure 4; Kobulnicky & Kewley 2004; Tremonti et al. 2004). The two hosts with $M_B \approx -18$ mag have $12+\log(\mathrm{O/H}) \approx 8.6$, while those with $M_B \approx -20$ to -21 mag have $12+\log(\mathrm{O/H}) \approx 8.8-8.9$, following the general trend. On the other hand, the short GRB host metallicities are systematically higher than those of long GRB hosts, which have been argued to have lower than expected metallicities (Stanek et al. 2006). The median metallicity of short GRB hosts is about 0.6 dex higher than for long GRB hosts, and there is essentially no overlap between the two host populations.

5. SUMMARY AND CONCLUSIONS

We present optical spectroscopy of several short GRB host galaxies, and a complete compilation of all short GRBs with *Swift*/XRT positions (23 bursts). About one half of the sample has spectroscopically identified host galaxies, with $z \approx 0.1-1.1$. The ratio of star forming to elliptical galaxies in this spectroscopic sample is 5:1, regardless of whether we use only the objects with sub-arcsecond positions, or include those with XRT positions. We note that the maximum allowed fraction of elliptical galaxies in the *Swift*/XRT sample, assuming that all of the currently-unclassified hosts turn out to be ellipticals, is 55%. In the formulation of Zheng & Ramirez-Ruiz (2007), with a power law age distribution, $P(\tau) \propto \tau^n$ (where τ is the time delay between formation and merger), the range of early-to late-type ratios allowed by the data leads to $n \lesssim 1$; if the ratio is indeed $\sim 20\%$ then $n \lesssim -1$.

Despite the fact that most short GRBs occur in star forming galaxies, their properties are strongly distinct from those of long GRB hosts. The rest-frame *B*-band luminosity distribution of the short GRB hosts is systematically brighter than for long GRB hosts in the same redshift range. An even stronger difference is apparent in the specific star formation rates, with a median value for short GRB hosts that is nearly an order of magnitude lower than for long GRB hosts. Similarly, the metallicities of the short GRB hosts are about 0.6 dex higher than those of long GRB hosts, and unlike the long GRB hosts they follow the luminosity-metallicity relation of field galaxies. To the extent that the mean properties of the host galaxies reflect the identity of the progenitors, this clearly indicates that the progenitors of long and short GRBs are themselves distinct, supporting additional lines of evidence such as the

[6] We note that Prochaska et al. (2006) infer a metallicity of $12+\log(\mathrm{O/H}) \approx 8.2$ for GRB 050709, but their value is based on a different calibration of [NII]/Hα. Our inferred value allows for a self-consistent comparison with field galaxies and long GRB hosts.

lack of supernova associations in short GRBs.

On the other hand, a comparison to a large sample of star forming field galaxies in a similar redshift range reveals excellent agreement in terms of specific star formation rates and the luminosity-metallicity relation. Indeed, the K-S probability that the short GRB hosts are drawn from the field galaxy population is high, ≈ 0.6. Thus, short GRBs select galaxies that are representative of the average stellar populations at least to $z\sim 1$.

These comparisons, along with the presence of some short GRBs in elliptical galaxies, indicate that the progenitor ages span a wide range, $\sim 0.1-10$ Gyr. However, the overall dissimilarity to the hosts of long GRBs, which appear to be dominated by young stellar populations ($\lesssim 0.1$ Gyr; Christensen et al. 2004), indicates that only a small fraction of short GRBs ($\lesssim 1/3$) are likely to arise from a prompt population of progenitors. These conclusions provide additional support and constraints on the binary coalescence model of short GRBs, but are at odds with young progenitor populations such as magnetars.

We finally note that while nearly half of the short GRB hosts remain unclassified at present, the overall qualitative conclusion of our study – that short and long GRB hosts and hence the progenitors have a different distribution of properties – is robust. In particular, even if future spectroscopic observations of the unclassified hosts reveal that they are more similar to those of long GRBs, the overall dispersion in short GRB host properties will still be significantly larger than for long GRB hosts, both in terms of metallicities and specific star formation rates. Naturally, any population of short GRB hosts that is found to be similar to long GRB hosts may lead to the conclusion that some of the progenitors are related to a young stellar population (e.g., promptly merging binaries or magnetars); to reiterate, our current limit on such a population is $\lesssim 1/3$.

Looking forward, we expect to advance our understanding of the progenitors from three primary lines of host galaxy investigations. First, with a growing sample of short GRB hosts we will be able to assess whether the progenitor population is uniform, or perhaps exhibits a bimodal distribution, with a contribution from prompt (proportional to star formation) and delayed (proportional to stellar mass) components, as appears to be the case for type Ia supernovae (e.g., Sullivan et al. 2006). We expect the sample to grow both from new events, and from continued optical and near-IR spectroscopy of the existing hosts. Second, high angular resolution imaging with the *Hubble Space Telescope* can be used to investigate in detail the location of short GRBs within their host galaxies. This has already been done for GRB 050709, indicating that, unlike for long GRBs, the burst was not associated with a region of active star formation (Fox et al. 2005). Finally, absorption spectroscopy of short GRB afterglows, still unavailable in the present sample, will directly reveal the type of environment (disk, halo, intergalactic medium) in which the bursts explode. Taken together, these studies promise to shed light on the short GRB progenitor population(s), at least until the advent of sensitive gravitational wave detectors in the next decade.

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TABLE 1
SHORT GRB AND HOST GALAXY PROPERTIES

GRB	T_{90} (s)	F_γ (erg cm^{-2})	RA[a] (J2000)	Dec. (J2000)	Uncert. ($''$)	OA?	z	R[b] (mag)	L_B (L_*)	SFR ($M_\odot$/yr)	12+log(O/H)	Refs.
050509b	0.04	$(9.5\pm2.5)\times10^{-9}$	$12^h36^m13.58^s$	$+28^\circ59'01.3''$	9.3	N	0.226	16.75 ± 0.05	5	<0.1	···	1–2
050709	0.07	$(2.9\pm0.4)\times10^{-7}$	$23^h01^m26.96^s$	$-38^\circ58'39.5''$	0.4	Y	0.1606	21.05 ± 0.07	0.1	0.2	8.5	3–5
050724	3.0[c]	$(3.9\pm1.0)\times10^{-7}$	$16^h24^m44.36^s$	$-27^\circ32'27.5''$	0.5	Y	0.257	18.19 ± 0.03	1	<0.05	···	6–8
050813	0.6	$(1.2\pm0.5)\times10^{-7}$	$16^h07^m57.19^s$	$+11^\circ14'57.8''$	3.8	N	··· [d]	···	···	···	···	9–11
051210	1.27	$(8.1\pm1.4)\times10^{-8}$	$22^h00^m41.26^s$	$-57^\circ36'46.5''$	2.9	N	···	23.80 ± 0.15	···	···	···	12–13
051221a	1.40	$(1.2\pm0.1)\times10^{-6}$	$21^h54^m48.62^s$	$+16^\circ53'27.2''$	0.2	Y	0.5465	21.81 ± 0.09	0.3	1.0	8.8	14–15
060121	1.97	$(4.7\pm0.4)\times10^{-6}$	$09^h09^m51.99^s$	$+45^\circ39'45.6''$	0.1	Y	···	26.26 ± 0.30	···	···	···	13,16–17
060313	0.70	$(1.1\pm0.1)\times10^{-6}$	$04^h26^m28.42^s$	$-10^\circ50'39.9''$	0.2	Y	···	24.83 ± 0.20	···	···	···	13,18
060502b	0.09	$(4.0\pm0.5)\times10^{-8}$	$18^h35^m45.53^s$	$+52^\circ37'52.9''$	3.7	N	···	25.83 ± 0.05	···	···	···	13,19–21
060801	0.50	$(8.1\pm1.0)\times10^{-8}$	$14^h12^m01.35^s$	$+16^\circ58'53.7''$	2.4	N	1.1304	22.97 ± 0.11	0.6	6.1	···	13,22–24
061006	0.42	$(1.4\pm0.1)\times10^{-6}$	$07^h24^m07.66^s$	$-79^\circ11'55.1''$	0.5	Y	0.4377	22.65 ± 0.09	0.1	0.2	8.6	13,25–27
061201	0.8	$(3.3\pm0.3)\times10^{-7}$	$22^h08^m32.09^s$	$-74^\circ34'47.1''$	0.2	Y	··· [e]	···	···	···	···	28
061210	0.19	$(1.1\pm0.2)\times10^{-6}$	$09^h38^m05.27^s$	$+15^\circ37'17.3''$	1.8	N	0.4095	21.00 ± 0.02	0.9	1.2	8.8	13,29
061217	0.21	$(4.6\pm0.8)\times10^{-8}$	$10^h41^m39.32^s$	$-21^\circ07'22.1''$	3.8	N	0.8270	23.33 ± 0.07	0.4	2.5	···	13,30
070429b	0.5	$(6.3\pm1.0)\times10^{-8}$	$21^h52^m03.84^s$	$-38^\circ49'42.4''$	6.2	N	0.9023	23.22 ± 0.10	0.6	1.1	···	31
070707	1.1	$(1.4\pm0.2)\times10^{-6}$	$17^h50^m58.55^s$	$-68^\circ55'27.2''$	0.5	Y	···	>24.4	···	···	···	32–33
070714a	2.0	$(1.5\pm0.2)\times10^{-7}$	$02^h51^m43.10^s$	$+30^\circ14'34.2''$	3.2	N	···	···	···	···	···	34
070714b	3[f]	$(7.2\pm0.9)\times10^{-7}$	$03^h51^m22.30^s$	$+28^\circ17'50.8''$	0.4	Y	0.9230	24.92 ± 0.23	0.1	0.4	···	31,35–36
070724	0.4	$(3.0\pm0.7)\times10^{-8}$	$01^h51^m13.96^s$	$-18^\circ35'40.1''$	2.2	N	0.4571	20.53 ± 0.03	1.4	2.5	8.9	37–39
070729	0.9	$(1.0\pm0.2)\times10^{-7}$	$03^h45^m16.04^s$	$-39^\circ19'19.9''$	2.5	N	···	23.32 ± 0.23	···	···	···	40–41
070809	1.3	$(1.0\pm0.1)\times10^{-7}$	$13^h35^m04.41^s$	$-22^\circ08'28.9''$	4.8	N	···	24.86 ± 0.27	···	···	···	42–43
071227	1.8	$(2.2\pm0.3)\times10^{-7}$	$03^h52^m31.26^s$	$-55^\circ59'03.5''$	0.3	Y	0.3940	20.54 ± 0.03	1.2	···	···	44–46
080123	0.4	$(5.7\pm1.7)\times10^{-7}$	$22^h35^m46.10^s$	$-64^\circ54'03.2''$	2.1	N	···	···	···	···	···	47

NOTE. — Properties of the short GRBs and their host galaxies discussed in this paper, including (i) GRB name, (ii) duration, (iii) fluence, (iv-vi) position of the X-ray or optical afterglow including uncertainty, (vii) whether an optical afterglow was detected, (viii) spectroscopic redshift, (ix) host galaxy R-band magnitude corrected for Galactic extinction (Schlegel et al. 1998), (x) rest-frame B-band luminosity, (xi) star formation rate, (xii) metallicity, and (xiii) relevant references.

[a] All XRT positions are from the catalogs of Butler (2007) and Goad et al. (2007).

[b] Corrected for Galactic extinction (Schlegel et al. 1998).

[c] The light curve is dominated by a 0.25 s hard spectrum spike, with a BATSE duration of T_{90} = 1.3 s.

[d] The XRT error circle contains a single galaxy with red optical and near-IR colors indicative of an early-type galaxy at a photometric redshift of ~ 1.8 (Berger 2006b). However, no spectroscopic confirmation is available.

[e] The nature of the host galaxy remains unclear, given the location of an Abell cluster at $z = 0.0865$ about $8'$ away (Berger 2007), a galaxy at $z = 0.111$ about $17''$ away (Berger 2006a; Stratta et al. 2007), and a faint galaxy of unknown redshift $\lesssim 1''$ away. All three associations have a statistical significant of about 10%. We note that the galaxy at $z = 0.111$ has a specific star formation rate of 1.2 $M_\odot$ yr^{-1} L_*^{-1} (Stratta et al. 2007), in good agreement with the host sample presented in this paper. In addition, we measure for this galaxy a luminosity of $M_B \approx -19.1$ mag and a metallicity of $12+\log(O/H) = 8.8\pm0.2$, in excellent agreement with the luminosity-metallicity relation.

[f] The light curve is dominated by a short and hard initial spike, with a small spectral lag (Racusin et al. 2007).

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TABLE 2
EMISSION LINE FLUXES AND METALLICITY INDICATORS

GRB	$F_{[OII]}$	$F_{[OIII]}$	$F_{H\beta}$	$F_{H\alpha}$	$F_{[NII]}$	$\log(R_{23})$	$\log(O_{32})$	$12+\log(O/H)$[a]	Refs.
	(10^{-17} erg cm^{-2} s^{-1})								
061006	4.1	1.5	0.9	···	···	0.79	–0.44	8.63	This paper
061210	22	10.5	7.6	11	2.4	0.63	–0.32	8.82	This paper
070724	37	17	15	···	···	0.56	–0.34	8.88	This paper
050709	···	26	6.6	26	1.8	···	···	8.50	1
051221a	10.3	5.9	3.9	···	···	0.62	–0.24	8.84	2

NOTE. — Emission line fluxes and metallicity indicators. The quantities R_{23} and O_{32} are defined in §3.3.
[a] The typical uncertainty on the metallicity is about 0.1 dex, dominated by the systematics in the R_{23} and O_{32} calibrations (Kobulnicky & Kewley 2004).
References: [1] Fox et al. (2005); [2] Soderberg et al. (2006).

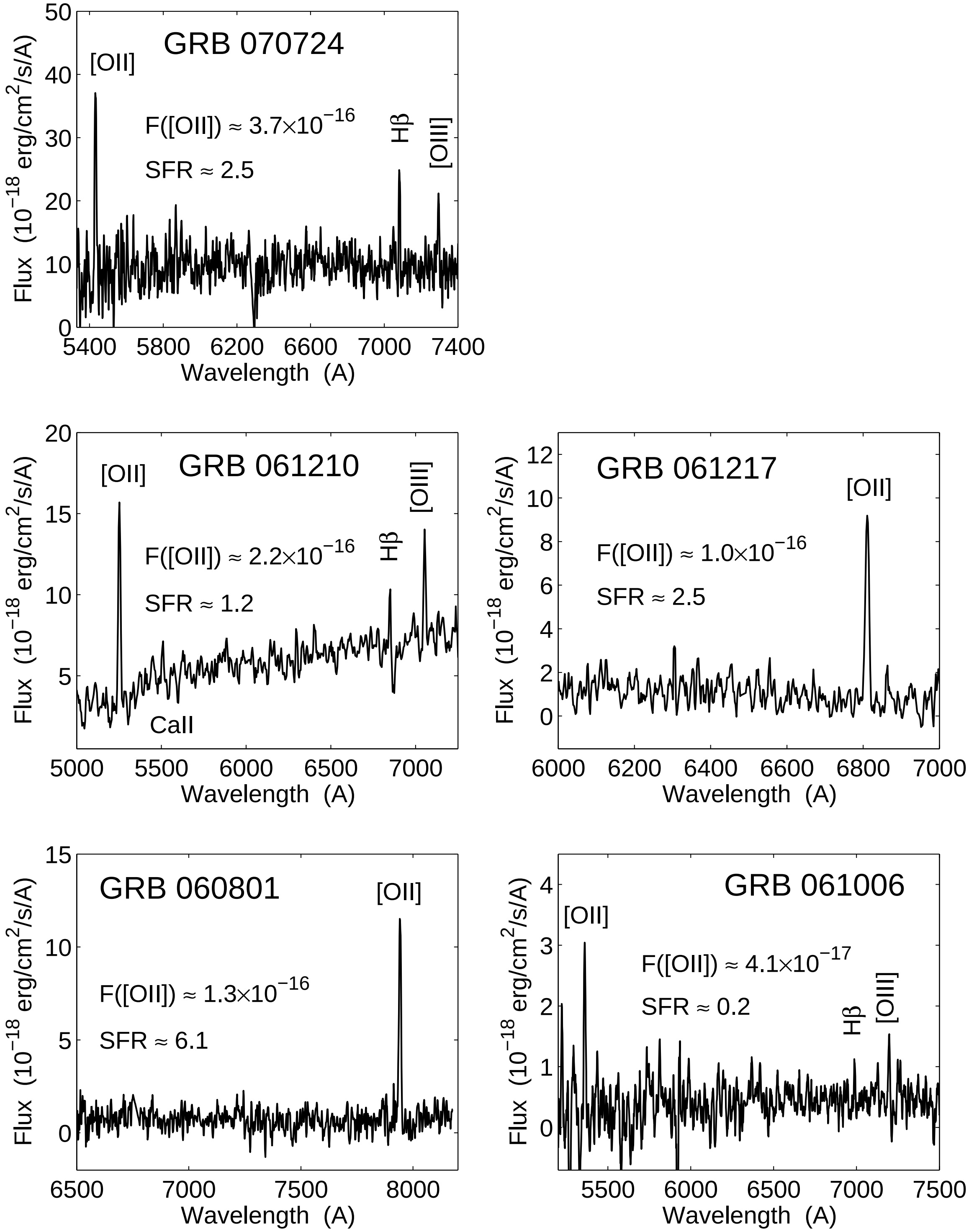

FIG. 1.— Optical spectra of short GRB host galaxies obtained with Gemini/GMOS and Magellan/LDSS3. For details see §2 and Berger et al. (2007b). The relevant emission lines are marked, and star formation rates from the [OII]λ3727 doublet are provided.

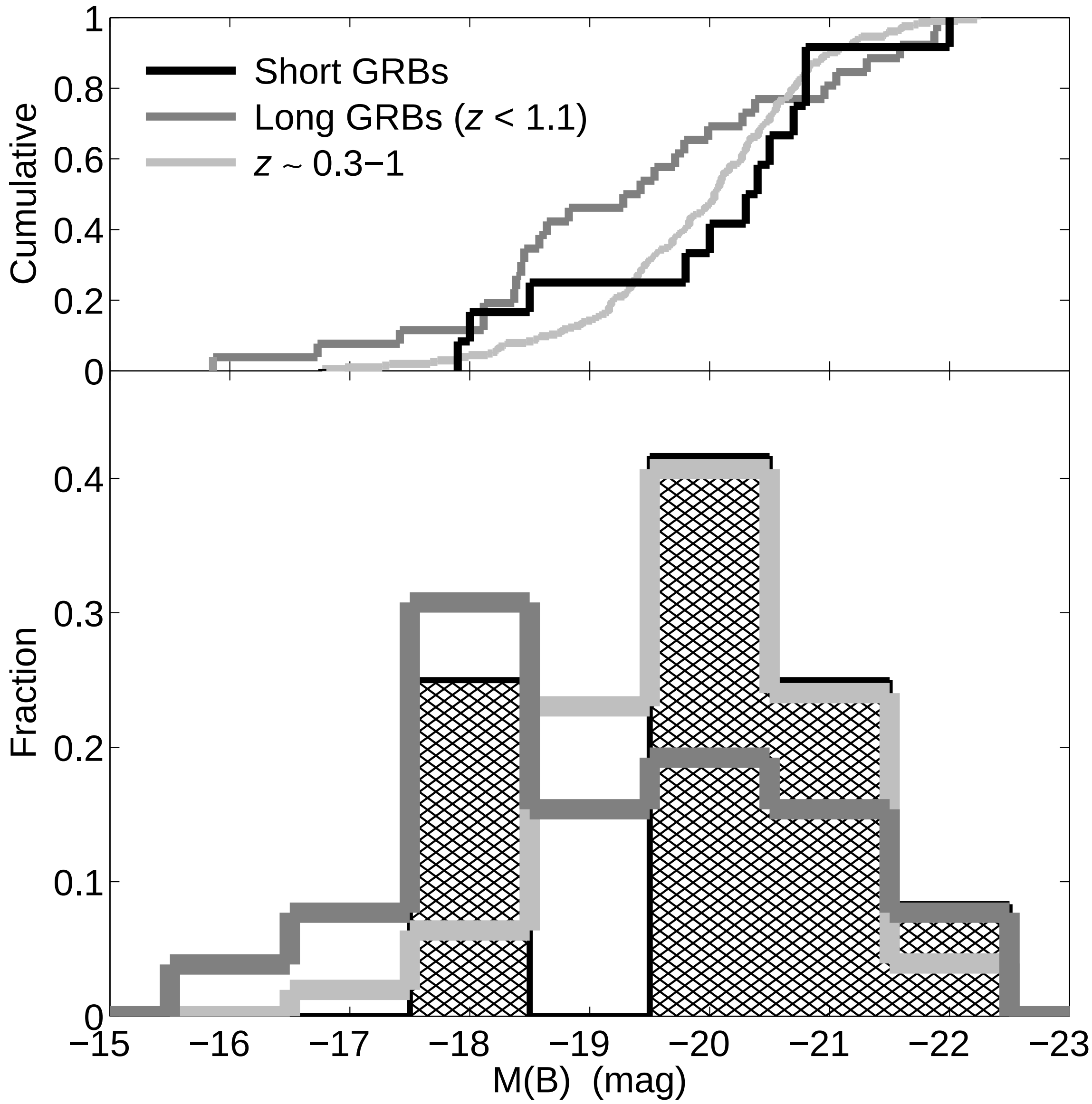

FIG. 2.— Distribution of *B*-band absolute magnitudes for the hosts of short (black) and long (dark gray) GRBs, as well as field star forming galaxies from the GOODS-N survey (light gray; Kobulnicky & Kewley 2004). A K-S test of the cumulative distributions (top) indicates a probability of only 10% that the short GRB hosts are drawn from the same distribution of long GRB hosts, and 60% that they are drawn from the field galaxy distribution.

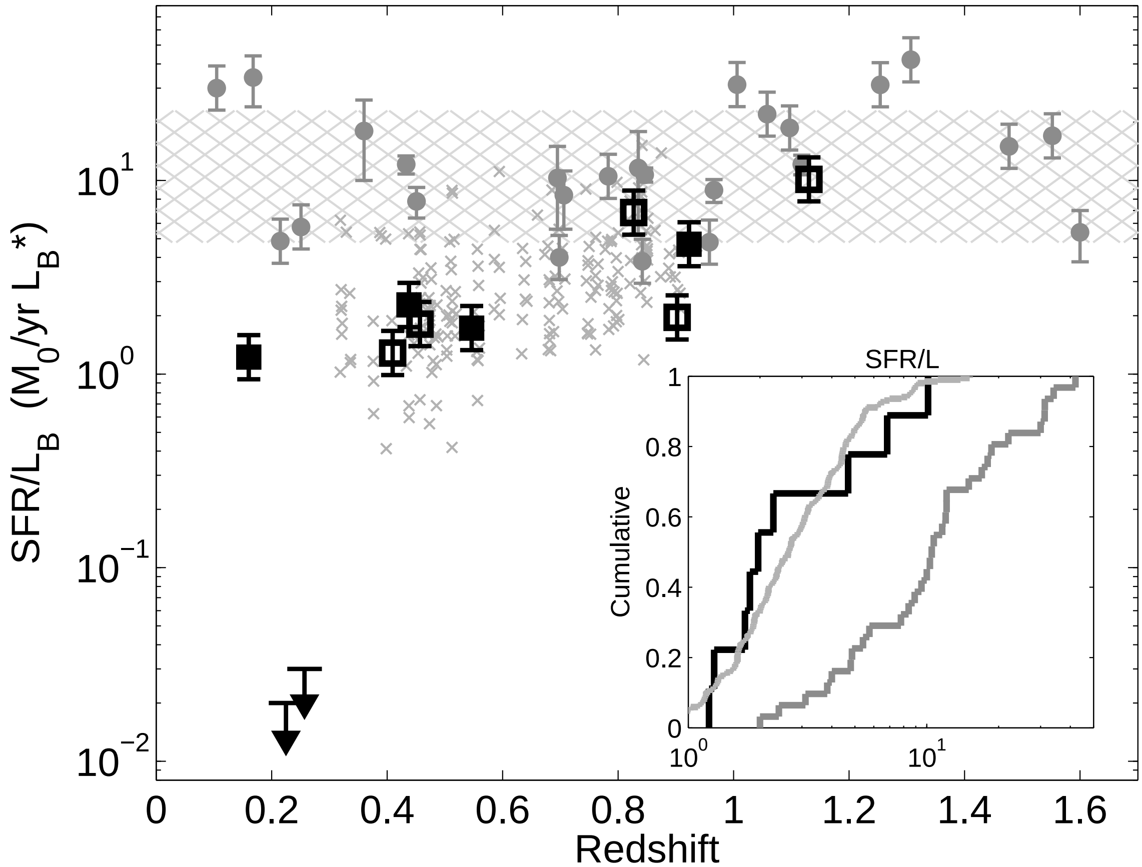

FIG. 3.— Specific star formation rates as a function of redshift for the host galaxies of short (black) and long (gray) GRBs, as well as field galaxies from the GOODS-N survey (crosses; Kobulnicky & Kewley 2004). Solid and open symbols designate short GRBs with sub-arcsecond positions and XRT positions only, respectively. Upper limits for the elliptical hosts of GRBs 050509b and 050724 are also shown. The cross-hatched region marks the median and standard deviation for the long GRB host sample. The inset shows the cumulative distributions for the three samples. The K-S probability that the short and long GRB hosts are drawn from the same distribution is only 0.3%, while the strong overlap with the field sample leads to a K-S probability of 60%.

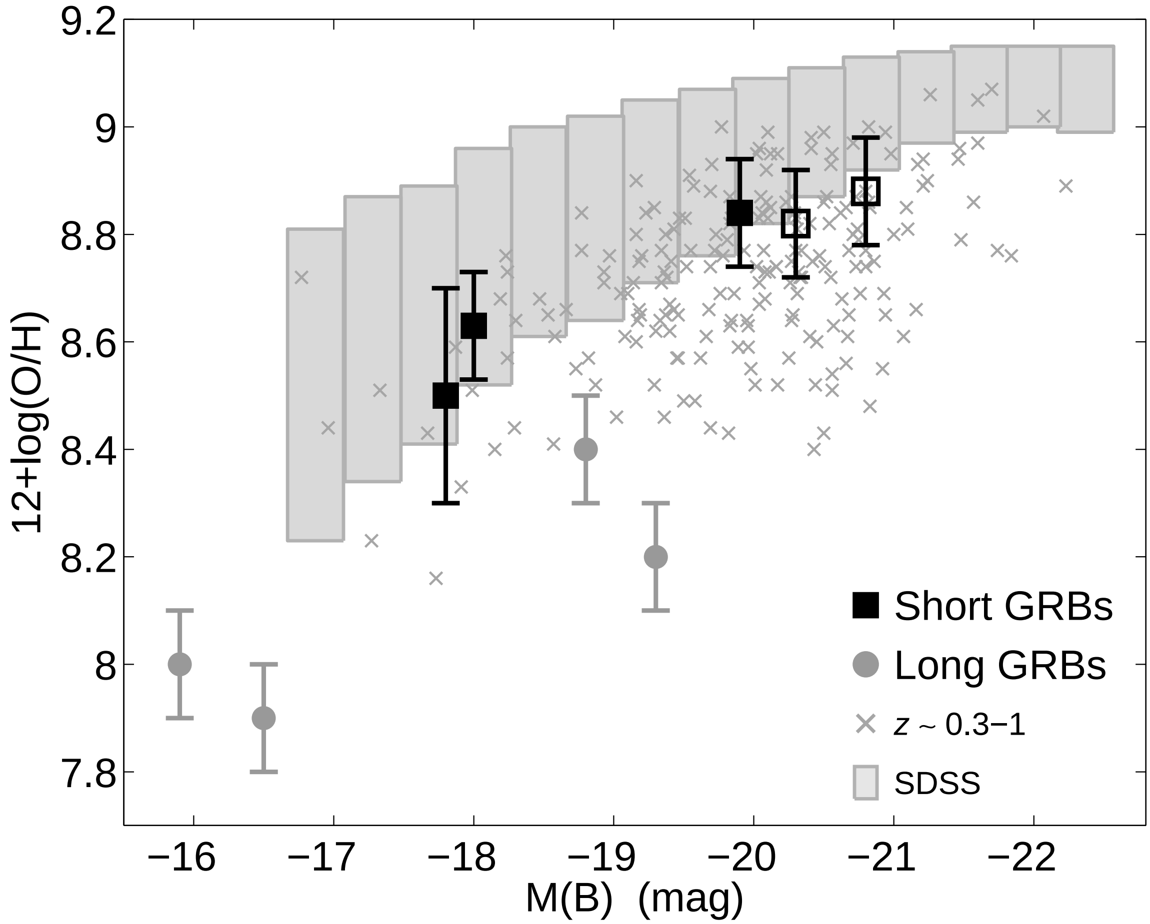

FIG. 4.— Metallicity as a function of *B*-band absolute magnitude for the host galaxies of short (black) and long (gray) GRBs. The gray bars mark the 14 − 86 percentile range for galaxies at $z \sim 0.1$ from the Sloan Digital Sky Survey (Tremonti et al. 2004), while crosses designate the same field galaxies at $z \sim 0.3-1$ shown in Figure 3 (Kobulnicky & Kewley 2004). Both field samples exhibit a clear luminosity-metallicity relation. The long GRB hosts tend to exhibit lower than expected metallicities (Stanek et al. 2006), while the hosts of short GRBs have higher metallicities by about 0.6 dex, are moreover in excellent agreement with the luminosity-metallicity relation.